Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications

2008 DOE Hydrogen Program Review

Project ID # FC8

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Overview

TIAX has performed PEMFC cost assessments for many years supported by DOE. This current project was initiated in 2006.

Timeline

- Start date: Feb 2006
- Base period: May 2008
  - » 100% complete
- Option period: May 2011

Barriers

- Barriers addressed
  - » A. Cost

	Cost Targets ($/kW)		
	2005	2010	2015
Fuel Cell System	110	45	30
Fuel Cell Stack	70	25	15

* *Manufactured at volume of 500,000 per year.*

Budget

- Total project funding
  - » Base Period = $415K
  - » No cost share, no contractors
- FY07 = $214K
- FY08 = TBD

Partners

- Project lead: TIAX
- Collaborate with ANL on system configuration and modeling
- Feedback from Fuel Cell Tech Team, Developers, Vendors

ANL = Argonne National Lab

Objectives

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Overall	◆ Bottom-up manufacturing cost assessment of 80 kW direct-H_2 PEMFC system for automotive applications
2007	◆ High-volume (500,000 units/year) cost projection of ANL 2007 PEMFC system configuration assuming an NSTFC-based MEA and a 30 μm 3M-like membrane ◆ Bottom-up manufacturing cost analysis of BOP components (Bottom-up stack cost analysis competed in FY 2007) ◆ Sensitivity analyses on stack and system parameters ◆ EOS impacts on 2007 BOP costs (EOS analysis of 2005 stack completed in FY2006)
2008–2011	◆ Annual updates of high-volume cost projection ◆ Optional: specific analysis topics including cost implications of: » Ambient versus pressurized operation » High temperature, low humidity operation » Lower temperature, low humidity hydrocarbon membrane » Alternative PEMFC approaches including cell/stack constructions and BOP components » Other topics as the need arises

BOP = Balance-of-Plant
NSTFC = Nano-Structured Thin Film Catalyst
MEA = Membrane Electrode Assembly
EOS = Economies of Scale

Manufacturing cost estimation involves technology assessment, cost modeling, and industry input to vet assumptions and results.

Technology Assessment

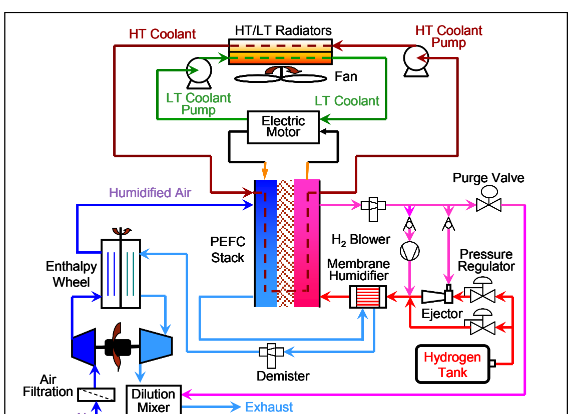
- Perform Literature Search
- Outline Assumptions
- Develop System Requirements and Component Specifications
- Obtain Developer Input

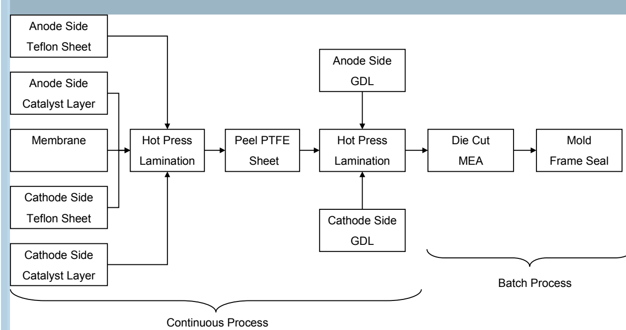
Cost Model and Estimates

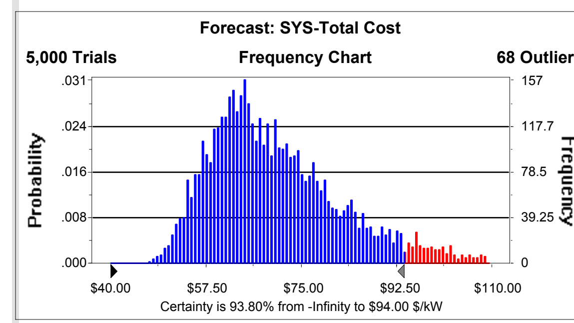
- Develop Bulk Cost Assumptions
- Develop BOM
- Specify Manufacturing Processes and Equipment
- Determine Material and Process Costs

Overall Model Refinement

- Obtain Developer and Industry Feedback
- Revise Assumptions and Model Inputs
- Perform Sensitivity Analyses

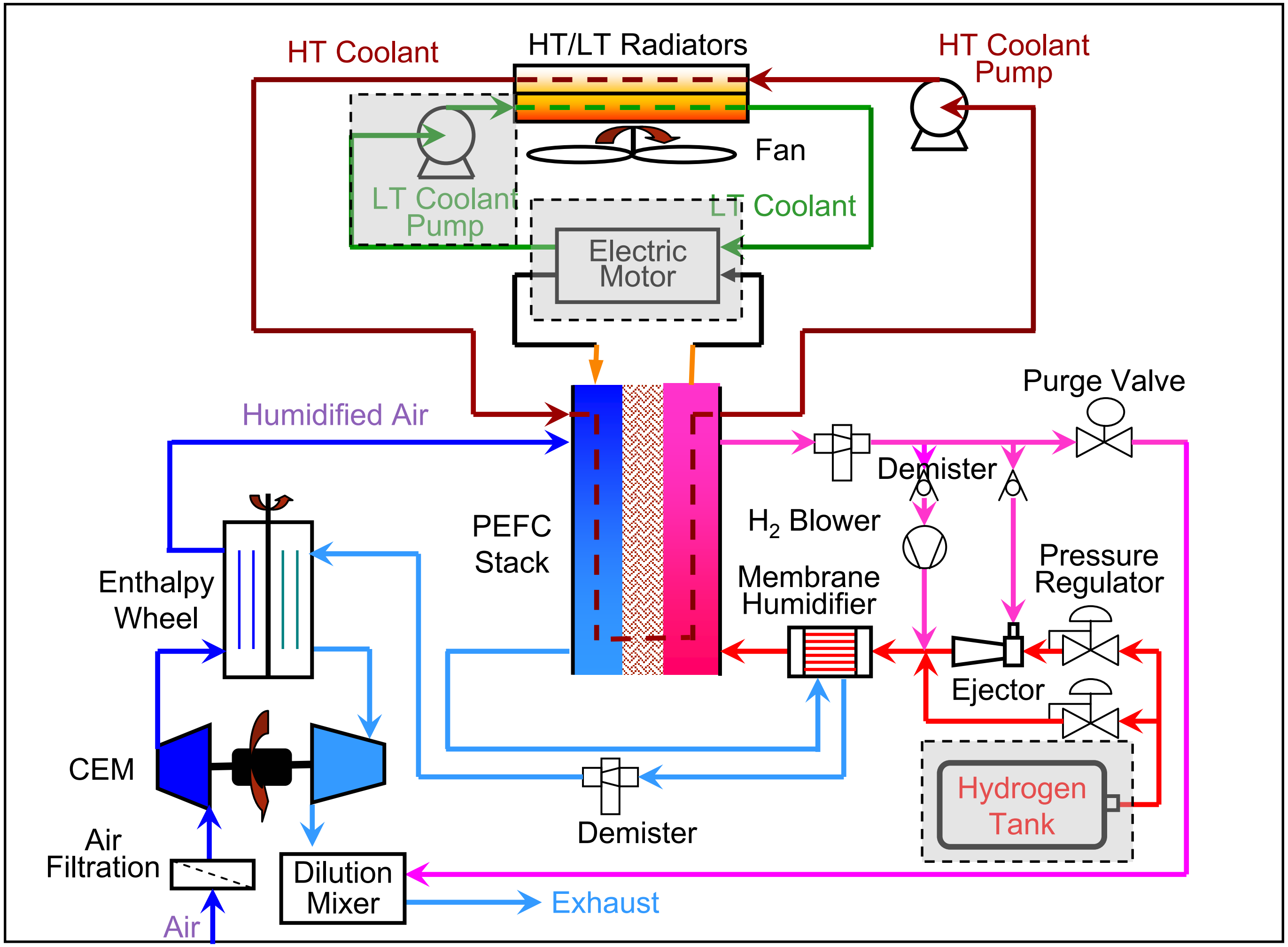






BOM = Bill of Materials

We worked with Argonne National Laboratory (ANL) to define the 2007 system configuration, performance and component specifications[1].



Not included in the fuel cell system cost assessment

[1] R.K. Ahluwalia and X. Wang, Reference Fuel Cell System Configurations for 2007: Interim Results, ANL, Feb. 6, 2007

We contacted developers of key stack and BOP components for their feedback on design, performance and cost assumptions.

Contacted in 2005-2006

- MEA
  - 3M, DuPont, Gore
- GDL
  - E-Tek
  - SpectraCorp, Toray, SGL Carbon
- Bipolar Plates
  - Porvair, GrafTech, SGL Carbon
  - Raw Materials - Superior Graphite, Asbury Carbons
- Seals
  - Freudenberg, SGL Carbon
- Stack and System Integrators
  - Ballard
  - Tech Team (GM, Ford, Chrysler)

Contacted in 2007

- MEA
  - 3M
- Water Management
  - PermaPure (Nafion membrane-based)
  - Emprise (enthalpy wheel)
- Thermal Management
  - Modine
- Air Management
  - Honeywell (compressor-expander-motor)
- Fuel management
  - Parker Hannifin
  - H_2 Systems

We used two different bottom-up costing tools to perform the cost analysis on the BOP components.

Costing Tools

- TIAX Technology-Based Cost Model
  - Radiator
  - Enthalpy Wheel Humidifier
  - Membrane Humidifier
- DFMA® Concurrent Costing Software
  - Compressor Expander Module
  - H_2 Blower

TIAX Technology-Based Cost Model

- Defines process scenarios according to the production volume
- Easily defines both continuous as well as batch processes
- Breaks down cost into various categories, such as material, labor, utility, capital, etc.
- Assumes dedicated process line – yields higher cost at low production volumes

DFMA® Concurrent Costing

- Has a wide range of built-in manufacturing databases for traditional batch processes, such as casting, machining, injection molding, etc.
- Initially developed for the automobile industry; not well suited for processes used in manufacture of PEMFC stacks
- Does not assume dedicated process line – yields lower cost at low production volumes

For the EOS analysis, we developed three production scenarios - pilot plant, semi-scaled, and full-scaled - to represent a phased advance from proof-of-concept to mature manufacturing process.

- Pilot Plant
  - Low volume production
  - Proof-of-concept of the manufacturing process
  - Goal is to adapt the manufacturing process to high volume production
- Semi-Scaled
  - Low-to-medium volume production
  - Adapted manufacturing process
  - Goal is to validate the manufacturing process for high volume production
- Full-Scaled
  - High volume production
  - Mature manufacturing process
  - Goal is to sustain a low-cost, high-throughput, high-reliability manufacturing process

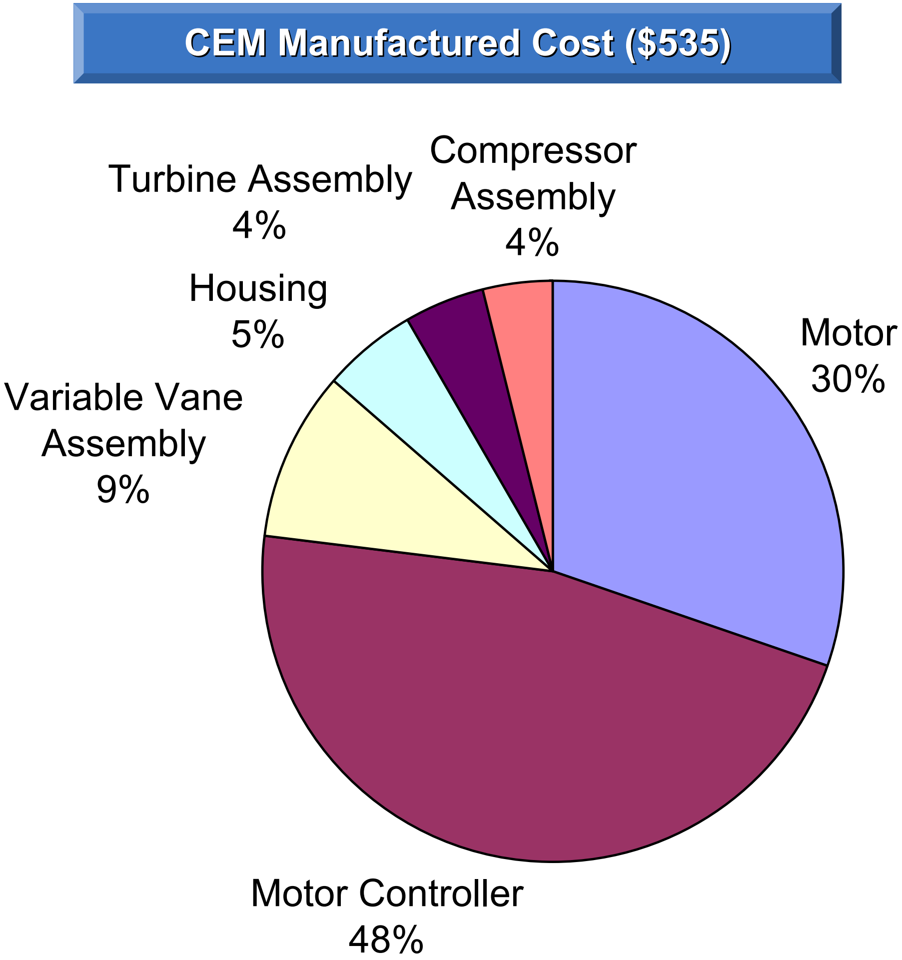
Material price, process type, process parameters, choice of equipment and level of automation (i.e. equipment capital cost) were varied across the three scenarios.

The high-volume factory cost for the BOP components is projected to be $1,350.

BOP Sub-system	Component	Technology Basis	Factory Cost[1], $ (without supplier markup)	OEM Cost[1], $ (with 15% supplier markup)
Water Management	Enthalpy wheel air-humidifier	Emprise	160	184
	Membrane H_2-humidifier	PermaPure	58	66
	Other	-	10	10
Thermal Management	Automotive tube-fin radiator	Modine	57	65
	Radiator fan[2]	-	35	35
	Coolant pump[3]	-	120	120
	Other	-	5	5
Air Management	Compressor-Expander-Motor (CEM)	Honeywell	535	615
	Other	-	97	97
Fuel Management	H_2 blower	Parker Hannifin	193	222
	H_2 ejectors[4]	-	40	40
	Other		41	41
TOTAL			1351	1500

[1] High-volume manufactured cost based on a 80 kW net power PEMFC system.
[2] Assumes $35/unit based on automotive radiator vendor catalog price, scaled for high volume production
[3] Assumes $120/unit, based on 2005 PEMFC Costing Report: E.J. Carlson et al., Cost Analysis of PEM Fuel Cell Systems for Transportation, Sep 30, 2005, NREL/SR-560-39104
[4] Assumes $20/unit, and 2 ejectors, based on 2005 PEMFC Costing Report: E.J. Carlson et al., Cost Analysis of PEM Fuel Cell Systems for Transportation, Sep 30, 2005, NREL/SR-560-39104

The CEM factory cost (without supplier markup) of $535, is the largest contributor to the overall BOP cost.



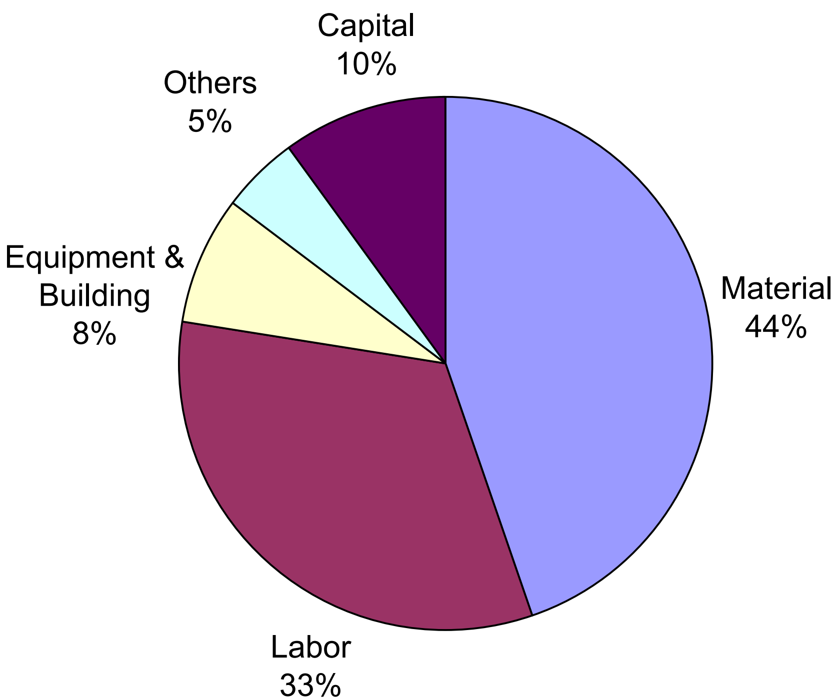
CEM Manufactured Cost ($)		
Component	**Factory Cost**	**OEM Cost[1]**
Motor	162	615
Motor Controller[2]	251	
Variable Vane Assembly	50	
Housing	28	
Turbine Assembly	24	
Compressor Assembly	21	
Total:	**535**	

[1] Assumes 15% markup to the automotive OEM

[2] $40/kW from "A Novel Bidirectional Power Controller for Regenerative Fuel Cells", Final Report for DE-FG36-04GO14329, J. Hartvigsen and S.K. Mazumder, Oct. 10, 2005

Process costs can be significant for BOP components. For example, material costs represent less than half the membrane humidifier cost.

Membrane Humidifier Manufactured Cost[1] ($58)



Membrane Humidifier Manufactured Cost[1] ($)			
Component	**#**	**Material**	**Process**
Right side housing	1	2.62	0.84
Small O-ring	2	1.00	0.00
Big O-ring	2	1.00	0.00
C-clip	2	0.20	0.00
Nafion tubes	960	14.19	22.42
Nafion tube housing	1	1.30	0.88
Nafion tube header	2	0.20	0.00
Mesh filter	2	0.20	0.00
Left side housing	1	2.85	0.85
Assembly & packaging	-	2.05	6.93
Subtotal	-	25.85	31.93
Total	**-**	**58**	

[1] High-volume manufactured cost (no supplier markup) based on a 80 kW net power PEMFC system. Estimates are not accurate to the number of significant figures shown.

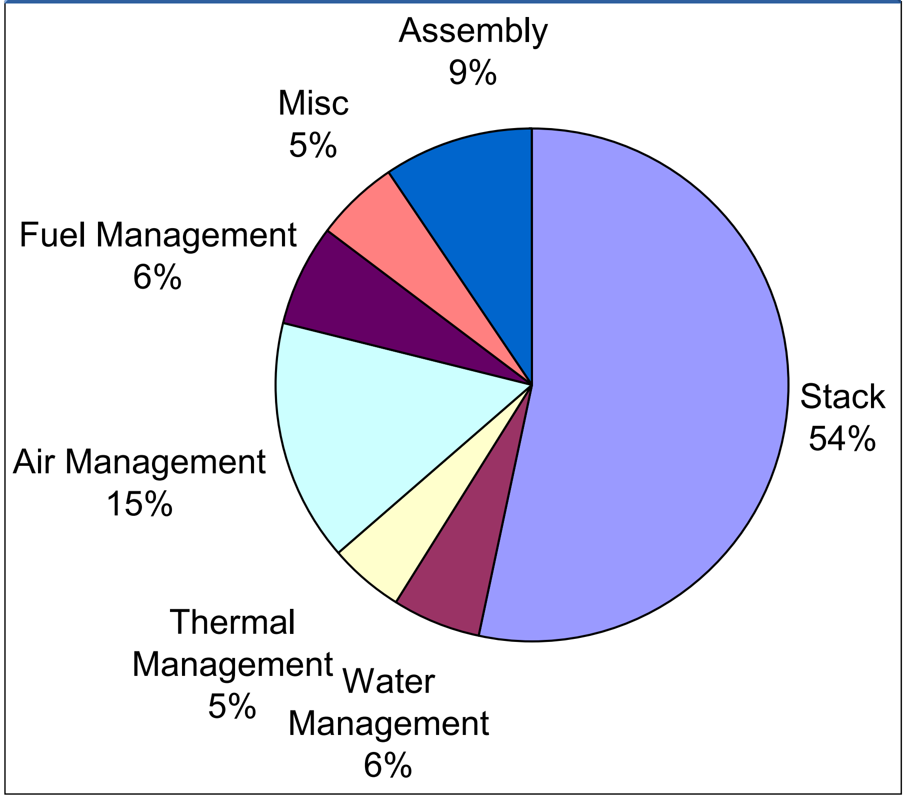
Both stack and BOP component costs are significantly reduced from the 2005 cost assessment.

PEMFC System Cost[1] ($/kW)	2005 OEM Cost	2007 Factory Cost[1]	2007 OEM Cost[1,2]
Stack	**67**	**31**	**31**
Water Management	8	2.8	3.3
Thermal Management	4	2.7	2.8
Air Management	14	7.9	8.9
Fuel Management	4	3.4	3.8
Miscellaneous	7	3.1	3.1
Assembly	4	5.5	5.5
Total	**108**	**57**	**59**

[1] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW).

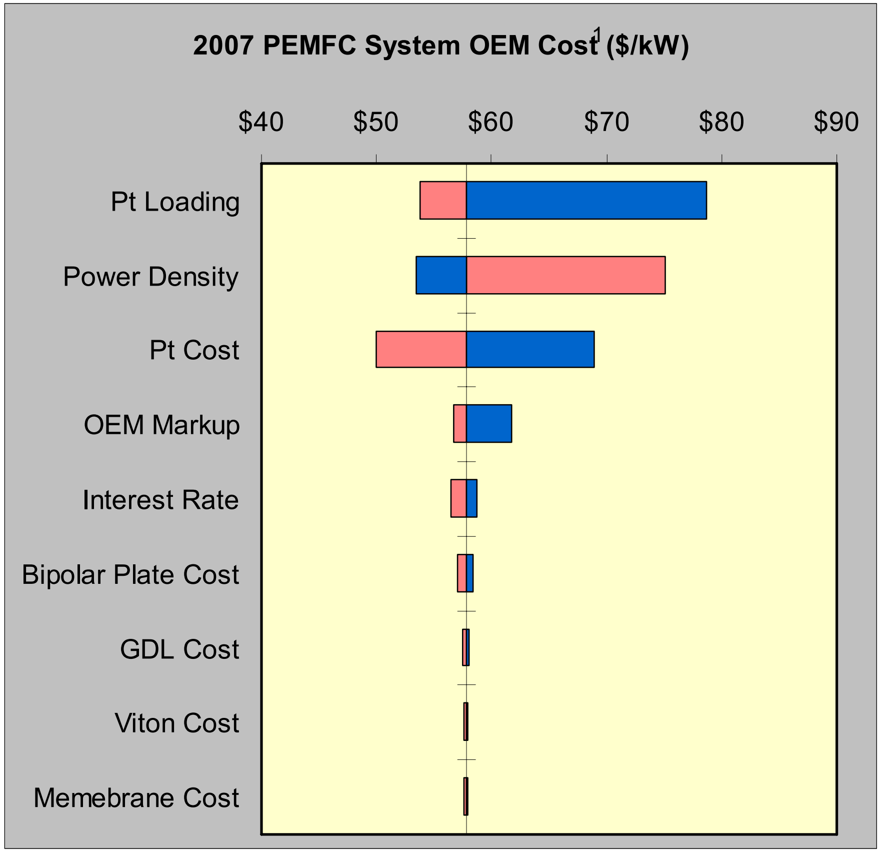
[2] Assumes 15% markup to the automotive OEM for BOP components

2007 PEMFC System OEM Cost[1,2] ($59/$kW_{net\ power}$, $4,720)



BOP component costs represent ~ 46% of the PEMFC system cost in 2007, as compared to ~ 38% in 2005.

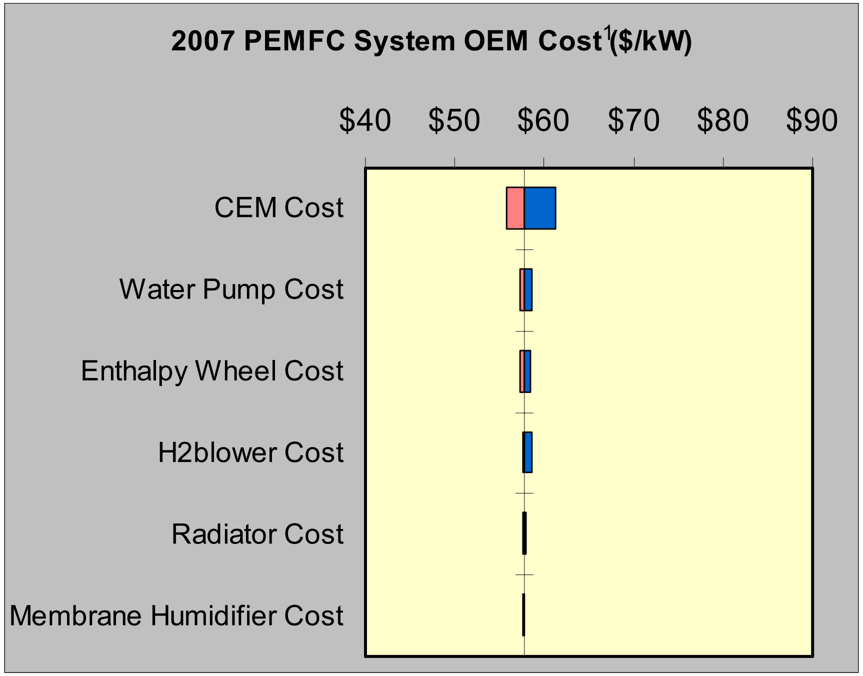
Pt loading, power density, and Pt cost are the top three cost drivers of the PEMFC system cost[1].



#	Variables	Minimum	Maximum	Base	Comments
1	Pt Loading (mg/cm^2)	0.2	0.75	0.3	Minimum: DOE 2015 target[2]; Maximum: TIAX 2005 study[3]
2	Power Density (mW/cm^2)	350	1000	753	Minimum: industry feedback; Maximum: DOE 2015 target[2].
3	Pt Cost ($/tr.oz.)	450	2000	1100	Minimum: historical average[4]; Maximum: current LME price[5]
4	OEM Markup	5%	20%	15%	Based on industry feedback
5	Interest Rate	8%	20%	15%	Based on industry feedback
6	Bipolar Plate Cost ($/kW)	1.8	3.4	2.6	Based on component single variable sensitivity analysis
7	GDL Cost ($/kW)	1.7	2.2	1.9	Based on component single variable sensitivity analysis
8	Viton Cost ($/kg)	39	58	48	Based on industry feedback
9	Membrane Cost ($/m^2)	10	50	16	Minimum: GM study[6]; Maximum: DuPont projection[7]

1. High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW). Assumes a % markup to automotive OEM for BOP components.
2. http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/fuel_cells.pdf
3. Carlson, E.J. et al., “Cost Analysis of PEM Fuel Cell Systems for Transportation”, Sep 30, 2005, NREL/SR-560-39104
4. www.platinum.matthey.com
5. www.metalprices.com
6. Mathias, M., ”Can available membranes and catalysts meet automotive polymer electrolyte fuel cell requirements?”, Am. Chem. Soc. Preprints, Div. Fuel Chem., 49(2), 471, 2004
7. Curtin, D.E., “High volume, low cost manufacturing process for Nafion membranes”, 2002 Fuel Cell Seminar, Palm Springs, (Nov 2002)

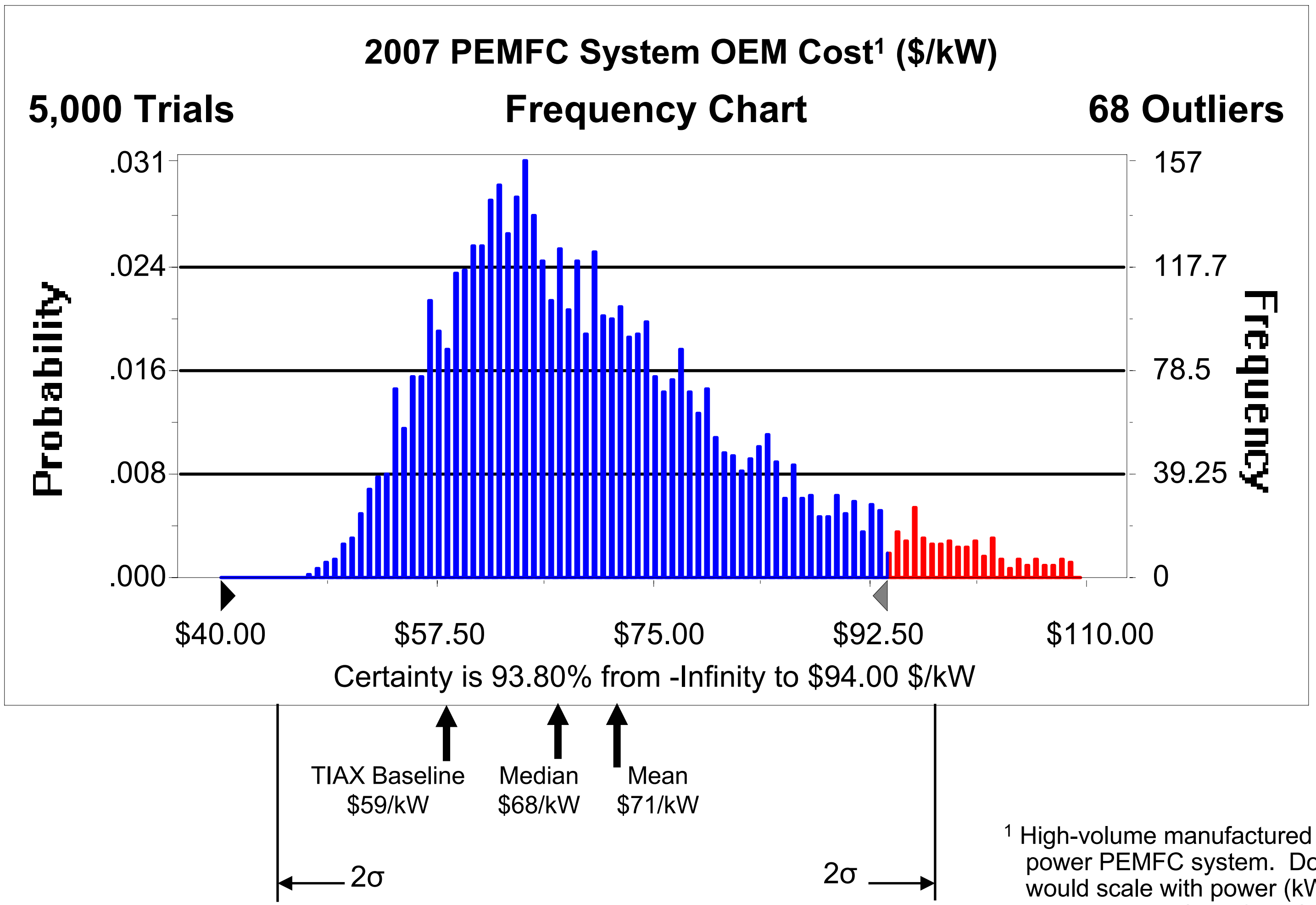
Among the BOP components, the CEM has the greatest impact on the PEMFC system cost[1].



#	Variables	Minimum	Maximum	Base	Comments
1	CEM Cost ($/unit)	368	808	535	Based on component single variable sensitivity analysis
2	Coolant Pump Cost ($/unit)	80	200	120	Based on industry feedback
3	Enthalpy Wheel Cost ($/unit)	123	217	160	Based on component single variable sensitivity analysis
4	H2 Blower Cost ($/unit)	178	259	193	Based on component single variable sensitivity analysis
5	Radiator Cost ($/unit)	46	71	56	Based on component single variable sensitivity analysis
6	Membrane Humidifier Cost ($/unit)	46	62	58	Based on component single variable sensitivity analysis

[1] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW). Assumes a % markup to automotive OEM for BOP components.

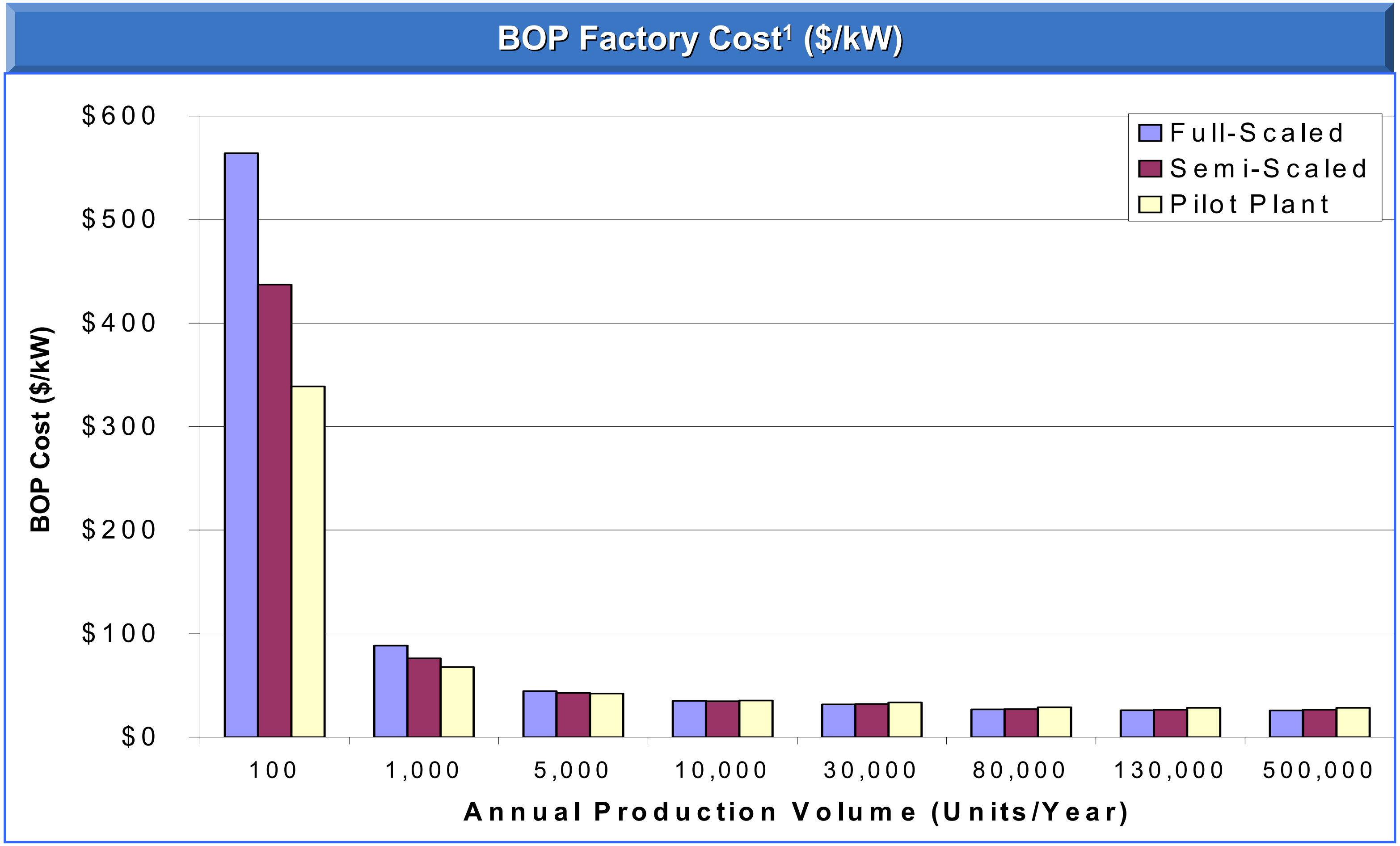
Monte Carlo analysis shows that the PEMFC system OEM cost ranges between $45/kW and $97/kW (± 2σ) at a production volume of 500,000 units per year.



Cost[1]	$/kW
Mean	71
Median	68
Std. Dev.	13
TIAX Baseline	59

[1] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW). Assumes a % markup to automotive OEM for BOP components.

At low production volumes (100 units/year), the pilot plant scenario yields the lowest BOP cost of $340/kW, while at high volumes (≥ 80,000 units/year), the full-scaled scenario yields the lowest BOP cost of $26/kW.



[1] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW).

Summary Comparison to Targets

The 2007 PEMFC stack and system costs are ~ 25-30% higher than the DOE 2010 cost targets.

PEMFC Sub-System	Factory Cost[1], \$/kW (without supplier markup)	OEM Cost[1,2], \$/kW (with 15% supplier markup)	DOE 2010 Cost Target[3], \$/kW
Stack	**31**		**25**
Balance of Plant	**26**	**28**	**20**
Water management (enthalpy wheel, membrane humidifier)	2.8	3.3	
Thermal management (radiator, fan, pump)	2.7	2.8	
Air management (CEM, motor controller)	7.9	8.9	5
Fuel management (H_2 blower, H_2 ejectors)	3.4	3.8	
Miscellaneous and assembly	8.6		
Total System	**57**	**59**	**45**

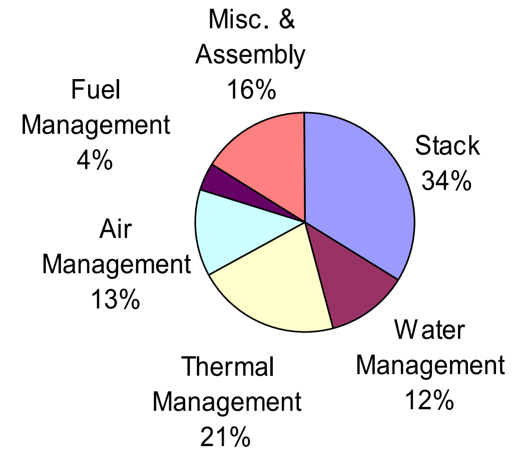
[1] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW).
[2] Assumes 15% markup to the automotive OEM for BOP components
[3] FreedomCAR targets are \$20/kW for the stack and \$35/kW for the total system.

While our focus is on cost, we also independently evaluated power density and specific power for the stack and system.

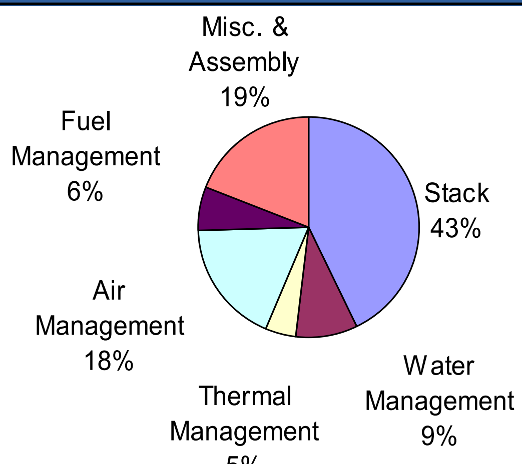
PEMFC Sub-System	Volume[1] (L)	Weight (kg)	DOE 2010 Target
Stack	**40**	**47**	
Power density[2] (W_e/L)	2,000		2,000
Specific power[2] (W_e/kg)	1,702		2,000
Balance of Plant	**78**	**63**	
Water management (enthalpy wheel, membrane humidifier)	14	10	
Thermal management (radiator, fan, pump)	25	5	
Air management (CEM, motor controller)	15	20	
Fuel management (H_2 blower, H_2 ejectors)	5	7	
Miscellaneous and assembly	19	21	
Total System	**118**	**110**	
Power density[2] (W_e/L)	678		650
Specific power[2] (W_e/kg)	727		650

[1] Does not include packing factor, which would lower volumetric power density.
[2] Based on stack net power output of 80 kW, and **not** on the gross power output of 86.5 kW

2007 PEMFC System Volume (118 L)



2007 PEMFC System Weight (110 kg)



Future Work

We will obtain industry feedback on our input assumptions and cost results and write a comprehensive, peer-reviewable report covering our 2007 PEMFC cost analysis.

- Interview developers and stakeholders for feedback on performance and cost assumptions and overall results
  - 2007 System high-volume cost
  - 2006 Stack economies-of-scale
  - 2007 BOP economies-of-scale
- Incorporate feedback into stack and BOP bottom-up cost models.
- Prepare a comprehensive report on the 2007 PEMFC cost analysis (high-volume, bottom-up stack and BOP cost)